HORN ARRAY EMITTER

TO THE COMMISSIONER OF PATENTS & TRADEMARKS:

Your petitioners, Elwood G. Norris and James J. Croft, III, citizens of the United States of America, whose post office addresses are 13824 San Sebastian Way, Poway, California 92064, and 13633 Quiet Hills Drive, Poway, California 92604, respectively, pray that letters patent may be granted to them as inventors for the improvement in a HORN ARRAY EMITTER, set forth in the following specification.

Priority of Provisional Patent Application No. 60/192,778 filed March 28, 2000 in the United States Patent Office is hereby claimed.

BACKGROUND OF THE INVENTION

Field of the Invention:

The present invention relates to ultrasonic emitters, and more particularly to ultrasonic emitters which include impedance matching structure such as acoustic transformers having a horn configuration.

Prior Art:

A variety of emitter devices have been developed which propagate ultrasonic energy. These include piezoelectric transducers, electrostatic emitters, mechanical drivers, etc. A challenge with the use of such devices in air is to provide impedance matching methods to enhance the efficiency of power transfer to the ambient air. For example, the wave impedance of a piezoelectric material such as barium titanate exceeds that of air by a factor of 10^5. This extreme impedance difference severely attenuates transmission into a propagated ultrasonic beam of energy into the air.

The use of acoustic horns as transformer devices is well known with respect to most sound systems for both audio and ultrasound frequencies. Extensive research has been done detailing preferred horn configurations for specific frequency ranges. Mathematical formulas are generally available to optimize the geometry of each application for a given frequency.

A publication by Fletcher and Thwaites entitled "Multi-horn Matching Plate for Ultrasonic Transducers" Ultrasonics 1992, Vol 30, No. 2., discloses the use of an array of

acoustic horns formed in a plate as an acoustic transformer for ultrasonic transmission into air. Based on this disclosure, Figure 1 shows a transducer aligned with a horn plate. A spacing gap between the emitter element and throats of the respective horns is illustrated and identified as a key element in optimizing the efficiency of the horn array for ultrasonic energy. By choosing a gap distance specifically selected for a given horn array, the publication suggests improvement of pressure gain in transducer output by 10 dB or better.

Despite enhancement of the effectiveness by this horn array system, there remain significant problems in impedance matching, particularly with ultrasonic emitters.

Many new applications of ultrasonic energy, including parametric speakers, are offering new opportunities which require high levels of efficiency in order to get a commercially acceptable audio output from ultrasonic emissions. Generally, these parametric applications depend on effective impedance matching to enable propagation of ultrasonic waves into the air as the nonlinear medium necessary for acoustic heterodyning.

OBJECTS AND SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide an ultrasonic emitter which is capable of enhanced coupling of emissions which offer even greater power conversion from emitter to surrounding air.

It is a further object to develop an emitter which facilitates propagation of an audio-modulated ultrasonic emission which can decouple in air to provide indirect audio output.

An additional object is to provide an integrated emitter and acoustic transformer which is capable of high efficiency coupling between the emitter and surrounding air environment.

A further object of this invention is to provide a parametric sound system having improved performance, particularly within low frequency ranges.

These and other objects are realized in a sonic emitter array with enhanced emitter-to-air acoustic coupling. The emitter array includes a plate support member having opposing first and second faces separated by an intermediate plate body. The plate body has a plurality of conduits configured as an array of acoustic horns, with each horn having a small throat opening at the first face and an intermediate horn section which diverges to a broad mouth opening at the second face. An emitter membrane is positioned in direct contact with the first face and extends across the small throat openings. The emitter membrane is biased for (i) applying tension to the membrane extending across the throat openings and (ii) displacing the membrane into a non-planar configuration. This non-planar, stretched configuration permits application of a sonic frequency to the membrane for propagation through the intermediate horn section and out the broad mouth opening at the second face.

Numerous specific embodiments can be implemented with a variety of emitters including an emitter having a PVDF (polyvinylidiene di-fluoride) membrane which operates in response to an applied voltage as an active driver element integrally coupled to the acoustic horn. Electrostatic and piezoelectric drivers can similarly be directly coupled to the acoustic horn. These devices are representative of a general methodology for developing a high efficiency acoustic coupling device for coupling ultrasonic emitters to a surrounding air environment, based on the steps of a) integrally attaching an emitter membrane at a small throat opening of an acoustic horn; b) applying sonic frequencies to the emitter membrane to generate sonic compression waves at the small throat opening of the acoustic horn; and c) propagating the sonic

compression wave through the acoustic horn for enhanced air coupling at a broad mouth of the horn.

Other objects and features will be apparent to those skilled in the art, based on the following detailed description, taken in combination with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

Figure 1 depicts a prior art example of an emitter configuration utilizing an array of horn transformers for acoustic coupling with air.

Figure 2 shows an elevational view of an integral emitter/horn array constructed in accordance with the subject invention.

Figures 3 is a cross-section view of a single horn.

Figure 4 is a detailed sectional view of the integrated emitter and throat of the horn.

Figures 5 through 8 graphically illustrate alternative embodiments demonstrating various methods of displacing the emitter membrane within the small throat opening.

Figure 9 graphically illustrates an application of the present invention as part of a parametric speaker system for generating audio frequencies from ultrasonic output

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The following discussion identifies numerous features that form part of the general invention of a horn array which is directly coupled to an emitter which includes an oscillating member for generating sonic waves. Those skilled in the art will appreciate that the specific embodiments disclosed hereafter are representative of the specific embodiments of the present

invention, and should not be deemed as limiting, except as sent forth in the accompanying claims.

A sonic emitter array 10 is illustrated in Figure 2. It comprises a plate support member 11 having opposing first and second faces 12 and 13 separated by an intermediate plate body 14. The plate 11 is preferably a rigid material (metal, ceramic, polymer, etc), and may be either conductive or nonconductive, depending on the method of driving an emitter membrane 20 directly coupled to the first face 12. The thickness of the plate will vary, depending on the acoustic coupling properties required for specific frequency ranges and particular applications. Generally, the plate thickness will be within the range of 1 millimeter (mm) to 20 mm. The selection of acoustical, electrical and physical properties will be discussed hereafter.

The plate body includes a plurality of conduits configured as an array of acoustic horns 30. Each horn has a small throat opening 31 at the second face 13 and an intermediate horn section 32 which diverges to a broad mouth opening 33 at the second face 12. The degree of flair in the intermediate horn section, as well as the size of the respective small throat and broad mouth openings 31 and 33 may be configured in accordance with conventional design parameters. These parameters will be balanced and optimized, depending upon the degree of directionality desired, the bandwidth response selected and the gain and coupling efficiency intended. Detailed design considerations are therefore deemed unnecessary for enablement of the present disclosure. Representative dimensions illustrated in Figure 2 are a 10 mm diameter for the mouth 33, 2 mm diameter for the throat opening, and 10 mm for length or thickness of the plate.

In the illustrated embodiment, the array of horns comprise conduits which are molded to a desired shape within the plate support member for acoustic coupling of ultrasonic frequencies

to surrounding air. Appropriate techniques are well known within the injection molding industry for implementing these procedures. Alternatively, the array of horns may have conduits which are machined to the desired shape.

A preferred embodiment of the plate support member comprises circular plate as opposed to the rectangular shape illustrated in Figure 2. Such a configuration offers an emitted sound column of more uniform nature because of the common radius of the resulting beam output. Dimensions of the plate support member may vary; however, the diameter is generally at least three inches. The configuration may be planar or curved. A concave configuration enables selection of a curvature radius to minimize phase misalignment for a listener location at a predetermined distance from the emitter array. This is accomplished by adjusting the radius of curvature of the emitting face so that the distances from each mouth opening are common at a given listener location. Numerous other variations will be apparent to those of ordinary skill in the art.

Many forms of acoustic emitters may be coupled directly to the opening 31 at the throat of the horn. Selection of a specific emitter will be a function of the intended use of the horn array. Generally these emitters fall within two classes. The first class of emitters comprises those which function as the primary source of mechanical movement for development of compression waves. This class, referred to as acoustic drivers, includes an emitter membrane which is mechanically or physically displaced to create periodic compression waves in a direct or active mode. Examples of the first class of drivers includes piezoelectric emitters, mechanical oscillators, and similar structures which displace in response to energy supplied directly to the membrane. A preferred embodiment conceived as part of the present invention involves the use a film or flexible membrane made of PVDF material. This material has demonstrated surprising

utility with respect to direct generation of ultrasonic emissions as will be discussed hereafter. Because PVDF material responds directly to voltage variations, ultrasonic emissions can be directly generated at the small throat opening in a highly controlled manner.

The second class of emitters is characterized by passive or indirect power transmission, rather than in an active or direct mode. Electrostatic and magnetostrictive emitters are representative of this group. Operation of these emitters requires an independent drive source such as a variable voltage back plate or some other driver which passively or indirectly displaces the emitter mounted at the throat opening 31. For example, an electrostatic membrane having a conductive film may be directly coupled at the small opening 31, and pinched or otherwise biased into a state of tension. Ultrasonic electronic signals are applied to a conductive back plate which is electrically insulated from the membrane film, thereby coupling the ultrasonic signal to the electrostatic membrane for generating the desired compression waves through the horn.

Both classes of emitters are positioned in direct contact with the first face and extend across the small throat openings. This is somewhat counter to teachings of the prior art, which have required a displacement gap between the emitter and the small opening of the horn. The present inventors have discovered that by directly attaching the emitter at the first face 13 and in direct position at the throat of the horn develops a highly efficient ultrasonic emission source which couples surprisingly well with a surrounding air environment. Its operability as a parametric propagation source has been effectively demonstrated.

A biasing means is required for enabling the emitter membrane to properly function. This biasing means may be physically or inductively operative with respect to the emitter membrane, but must be capable of (i) applying tension to the membrane extending across the throat openings and (ii) displacing the membrane into a non-planar configuration. This is

represented in Figure 4 et.seq. by the slightly deformed or displaced emitter membrane 35 which is projecting within the small throat opening 31. The emitter membrane is part of a continuous membrane 20 which is disposed across the first face 13 of the plate support member. For example, the deformed emitter membrane 35 may be a preformed dimple positioned within the continuous membrane 20 and in alignment with the opening. The dimpled structure forms part of the biasing means as described above, and would be complemented with a tension force to place the emitter membrane in biased position which permits vibrating motion consonant with a desired ultrasonic signal.

A back plate 40 is positioned behind the membrane and adjacent the small throat openings, and may also serve as part of the biasing means. For example, corresponding dimples 41 can be formed on the back plate in proper alignment to force the emitter membrane within the small throat openings 31. A spacer element 43 may be inserted between the back plate 40 and the emitter membrane 20 to displace the emitter portion 35 from contact with the back plate 40. This may be enhanced by the capture of a pocket of air 45 as a cushion which provides displacement space for the emitter membrane 35. Where PVDF material comprises the emitter membrane, vibration displacements activated by a variable voltage source are of such small distances that the gap formed by the pocket of air 45 may be very small. Alternatively, an outside pressure source P may be applied as illustrated in Figure 5, wherein the emitter membrane is biased by positive pressure shown by arrows 47. In this case, the air pocket 48 is pressurized through a small conduit 49 which communicates with a plenum 50 or other pressurized source. This also permits uniform pressure on each member of the horn array, providing consistency in output between the respective emitter membranes 35.

The spacer element 43 may also be viewed as structure for clamping the membrane in fixed position around the small throat opening such that vibrational energy is not transferred through the membrane to adjacent horns. This same function is performed by the back plate in the absence of the spacer element. Isolation of each emitter element 35 is important for minimizing cross transmission of vibrations through the continuous membrane 20. The spacer and/or back plate also acts as a damping member to reduce vibrations carried through the plate support member 11 (Fig. 1). With each emitter membrane being supplied by a common voltage or energy source, and operating as a continuous membrane having uniform physical properties, the isolated emitter sections 35 can be tuned and electronically or mechanically activated to develop a uniform wave front with minimal distortion. The application of this emitter configuration with an array of horn-type acoustic transformers offers significant advantages over other emitter systems.

The back plate, as shown in Fig. 4, may also include protruding structure 41 aligned with each small throat opening as part of the biasing means. The protruding member operates to displace the emitter membrane slightly and/or to apply proper tension with sufficient displacement allow to activation as a sonic generator. Again, where PVDF material is used, the displacement distance is so nominal that the protruding portion need not extend more than 3 mm. Figures 4 through 8 illustrate various geometric shapes that are useful to displace the emitter membrane into the desired non-planar configuration.

The protruding structure 41 shown in Figure 4 comprises a convex bump having a size approximately equal to the small throat opening such that the bump projects within the throat of the horn. This configuration is very effective in isolating and developing uniform vibration response across the emitter section. The back plate includes means for developing a gap between

the convex bump and the membrane to allow vibrational displacement of the membrane when activated with the sonic frequency, thereby avoiding distorting contact with the convex bump. Typical dimensions of the convex bump include a radius of curvature of 10 - 30 mm and a height of 1 - 3 mm from the planar surface of the backplate.

An additional method for developing the required gap between the convex bump and the membrane comprises structure for supplying an electrostatic charge operable to repel the membrane from the bump during operation. This can be accomplished by establishing a baseline signal within the PVDF material which maintains a threshold tension, enabling the desired output signal to be applied for the generation of the sonic output in the emitter. It is possible to utilize a carrier signal for this biasing purpose, with sidebands providing the output signal. A similar biasing means can be developed with structure for supplying a magnetic force operable in a manner similar to the electrostatic embodiment to repel the membrane from the bump during operation.

As indicated above, a simple means for developing the required gap between the convex bump and the membrane may consist of a spacer ring positioned between the membrane and the back plate, with the bump being disposed in alignment with a central opening of the spacer ring. This spacer element is representative of numerous forms of mechanical means useful for displacing the emitter membrane from the backplate and bump. The thickness of the spacer will depend upon the range of frequency and amplitude of vibration of the emitter member. Typically, when operating within the ultrasonic range, spacer elements will vary in dimension from 1 to 3mm. Numerous materials may be selected, balancing such factors as insulative properties, damping constants, expansion coefficients, and chemical/mechanical compatibility with the backplate and the support plate.

Other forms of mechanical means for developing the gap between the back plate and the membrane are represented in Figures 6 to 8. These include a protruding structure having an apex configuration in contact with a central portion of the membrane to physically displace the membrane from the back plate. As an example, Figure 6 shows a conical structure 61 having an apex 62 in contact with a central portion of the membrane 63 to physically displace the membrane. A further embodiment shown in Figure 7 comprises a pin structure 71 having an apex 72 in contact with a central portion of the membrane 73. These embodiments may be provided with a spacer 43 to develop the desired gap between the back plate and membrane. The various shapes are to be considered as representative of the general concept that the emitter membrane can be mechanically displaced to provide the biasing and necessary gap for operation within the inventive concept.

Figure 8 illustrates the placement of the projecting element directly from the back plate without presence of a spacer for gap formation. Instead, a small projection 81 extends at a sufficient length to displace the membrane 83 away from the back plate 40 to provide space for vibration. With minimal displacements such as occur with higher ultrasonic frequencies, small gaps 84 on each side of the projection 81 are sufficient to enable operation of the emitter.

The present invention offers utility in many areas of sonic generation. It is particularly useful in coupling ultrasonic output to surrounding air. The efficiency of this system is most evident with respect to applications with parametric speaker systems where the signal source is coupled to an amplitude modulator for mixing audio frequencies with ultrasonic frequencies to develop an ultrasonic wave form with at least one sideband corresponding to the audio frequencies. The horn array propagates the combined carrier and sideband compression wave within the surrounding air environment which then decouples the audio frequencies to generate

audio output as part of an acoustic heterodyne speaker system. Such a system is illustrated in Figure 9.

This application utilizes a parametric or heterodyning technology, which is particularly adapted for the present thin film structure. The thin electrostatic film of the present invention is well suited for operation at high ultrasonic frequencies in accordance with parametric speaker theory.

A basic system includes an oscillator or digital ultrasonic wave source 104 for providing a base or carrier wave 108. This wave 108 is generally referred to as a first ultrasonic wave or primary wave. An amplitude modulating component 112 is coupled to the output of the ultrasonic generator 104 and receives the base frequency 108 for mixing with a sonic or subsonic input signal 116. The sonic or subsonic signal 116 may be supplied in either analog or digital form, and could be music from any convention signal source 120 or other form of sound. If the input signal 116 includes upper and lower sidebands 117, a filter component 124 may be included in the modulator to yield a single sideband output 118 on the modulated carrier frequency for selected bandwidths.

The diaphragm 100 is caused to emit the ultrasonic frequencies f_1 and f_2 as a new wave form 116 propagated at the face of the diaphragm 100. This new wave form interacts within the nonlinear medium of air 121 to generate the difference frequency 120, as a new sonic or subsonic wave. The ability to have large quantities of emitter sectors formed in an emitter horn array is particularly well suited for generation of a uniform wave front which can propagate quality audio output at meaningful volumes.

The present invention is able to function as described because the ultrasonic signals corresponding to f_1 and f_2 interfere in air according to the principles of acoustical heterodyning.

Acoustical heterodyning is somewhat of a mechanical counterpart to the electrical heterodyning effect which takes place in a non-linear circuit. For example, amplitude modulation in an electrical circuit is a heterodyning process. The heterodyne process itself is simply the creation of two new waves. The new waves are the sum and the difference of two fundamental waves.

In acoustical heterodyning, the new waves equaling the sum and difference of the fundamental waves are observed to occur when at least two ultrasonic compression waves interact or interfere in air. The preferred transmission medium of the present invention is air because it is a highly compressible medium that responds non-linearly under different conditions. This non-linearity of air enables the heterodyning process to take place, decoupling the difference signal from the ultrasonic output. However, it should be remembered that any compressible fluid can function as the transmission medium if desired.

Whereas successful generation of a parametric difference wave in the prior art appears to have had only nominal volume, the present configuration generates full sound. This full sound is enhanced to impressive volume levels because of the significant increase in coupling efficiency between the emitter diaphragm and the surrounding air.

The development of full volume capacity in a parametric speaker provides significant advantages over conventional speaker systems. Most important is the fact that sound is reproduced from a relatively massless radiating element. Specifically, there is no radiating element operating within the audio range because the film is vibrating at ultrasonic frequencies. This feature of sound generation by acoustical heterodyning can substantially eliminate distortion effects, most of which are caused by the radiating element of a conventional speaker. For example, adverse harmonics and standing waves on the loudspeaker cone, cone overshoot and

cone undershoot are substantially eliminated because the low mass, thin film is traversing distances in millimeters.

It should also be apparent from the description above that the preferred and alternative embodiments can emit sonic frequencies directly, without having to resort to the acoustical heterodyning process described earlier. However, the greatest advantages of the present invention are realized when the invention is used to generate the entire range of audible frequencies indirectly using acoustical heterodyning as explained above.

From a procedural perspective, the present invention may be viewed from the following method steps comprising: a) integrally attaching an emitter membrane at a small throat opening of an acoustic horn; b) applying sonic frequencies to the emitter membrane to generate sonic compression waves at the small throat opening of the acoustic horn; and c) propagating the sonic compression wave through the acoustic horn for enhanced air coupling at a broad mouth of the horn. The plate may be formed by preparing a plate support member having opposing first and second faces separated by an intermediate plate body. The plate body includes a plurality of conduits configured as an array of acoustic horns, each horn having a small throat opening at the first face and an intermediate horn section which diverges to a broad mouth opening at the second face. The emitter membrane is positioned in direct contact with the first face and extends across the small throat openings. Biasing means is provided to the emitter membrane for (i) applying tension to the membrane extending across the throat openings and (ii) displacing the membrane into a non-planar configuration. Finally, a sonic frequency is imposed on the membrane for propagation through the intermediate horn section and out the broad mouth opening at the second face.